Pentaquark Search at BNL

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What are penta-quarks?

- Minimum quark content is 5 quarks.
- "Exotic" penta-quarks are those where the antiquark has a different flavor than the other 4 quarks $\left(qqqq\bar{Q}\right)$
- Quantum numbers cannot be defined by 3 quarks alone.

Example: $uudd\bar{s}$

Baryon number = 1/3 + 1/3 + 1/3 + 1/3 – 1/3 = 1

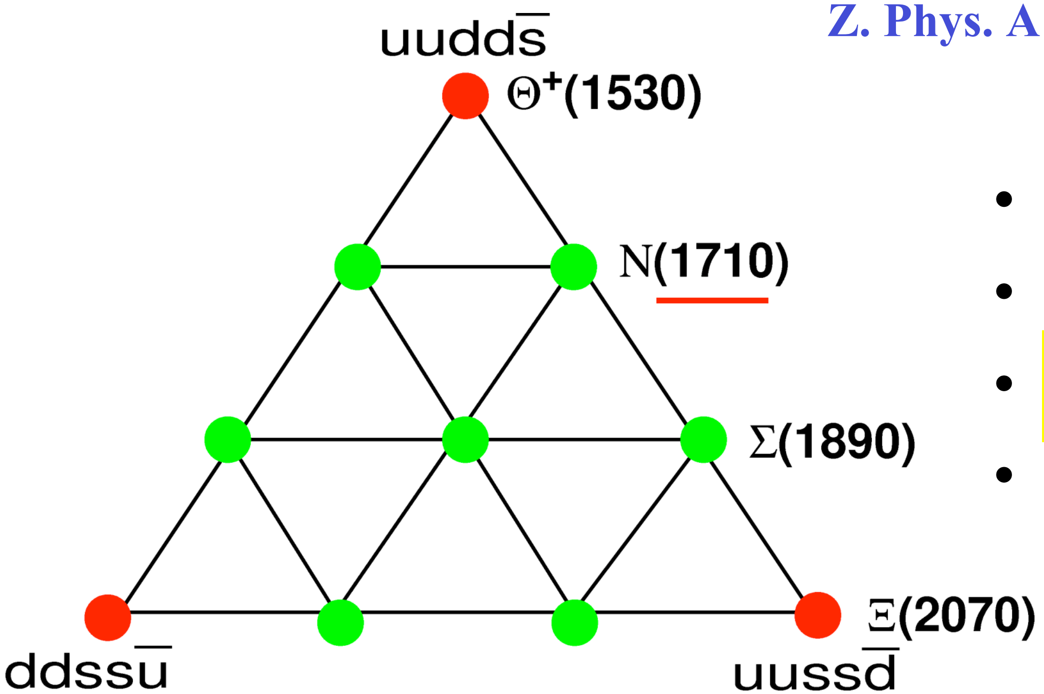
Strangeness = 0 + 0 + 0 + 0 + 1 = 1

e.g. $uudd\bar{c}$, $uuss\bar{d}$

c.f. L(1405): $uuds\bar{u}$ or uds

Q^+ Baryon

D. Diakonov, V. Petrov, and M. Polyakov,
Z. Phys. A 359 (1997) 305.



M = [1890-180*Y] MeV

- **Exotic: S=+1**
- **Low mass: 1530 MeV**
- **Narrow width: ~ 15 MeV**
- **J^p=1/2$^+$**

Baryon masses

- Mainly 3 quark baryons:

  M ~ 3Mq + (strangeness)

- 5-quark baryons, naively:

  M ~ 5Mq + (strangeness)

  1900 MeV for Q^+

- 5-quark baryons, in chiral quark soliton:

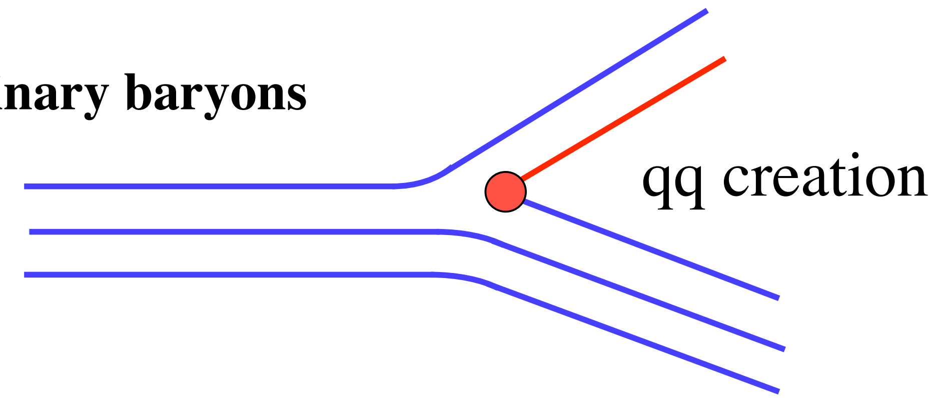
  M ~ 3Mq + 1/(baryon size) + (strangeness)

  ~1550 MeV for Q^+

Theory

- DPP predicted the Θ^+ with M=1530MeV, Γ<15MeV, and $J^p=1/2^+$.
- Naïve QM (and many Lattice calc.) gives M=1700~1900MeV with $J^p=1/2^-$.
- But the negative parity state must have very wide width (~1 GeV) due to "fall apart" decay.

Ordinary baryons

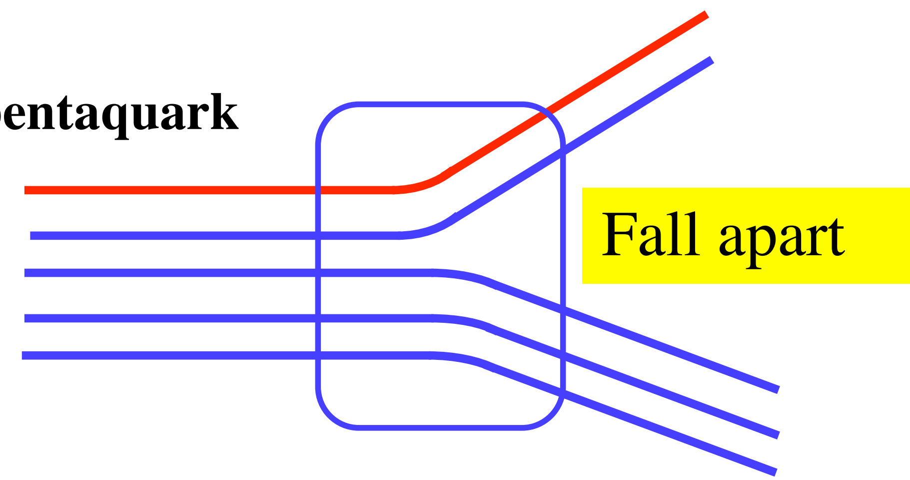


Positive Parity?

- Positive parity requires P-state excitation.
- Expect state to get heavier.
- Need counter mechanism.

diquark-diquark, diquark-triquark, or strong interaction with "pion" cloud?

For pentaquark



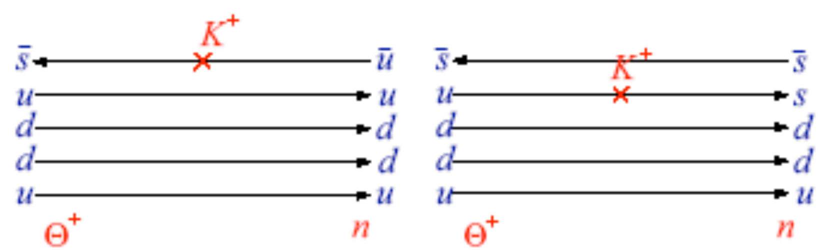
Why Q+ is so narrow?

$\Theta^+ \to nK^+$ decay

$$\Gamma_\Theta = \frac{3\,g^2_{\mathrm{KN\Theta}}}{2\pi[m_N + m_\Theta]^2}\frac{m_N}{m_\Theta}\frac{1}{5}\,|\mathrm{p}|^3$$

$$g_{\mathrm{KN\Theta}} \approx \frac{g_A^{\Theta\to\mathrm{NK}}\,(m_N + m_\Theta)}{2\,F_K} \qquad \text{similar to} \quad g_{\pi\mathrm{NN}} = \frac{g_A\,m_N}{F_\pi}$$

$$g_A^{\Theta^+\to nK^+} = \frac{<n^{(5)}|J_{05}^{K^+}|\Theta^+> + \ldots}{\sqrt{\mathcal{N}_n^{(3)} + \mathcal{N}_n^{(5)} + \ldots}\,\sqrt{\mathcal{N}_\Theta^{(5)} + \ldots}}, \qquad \frac{\mathcal{N}_n^{(5)}}{\mathcal{N}_n^{(3)}} \ll 1$$

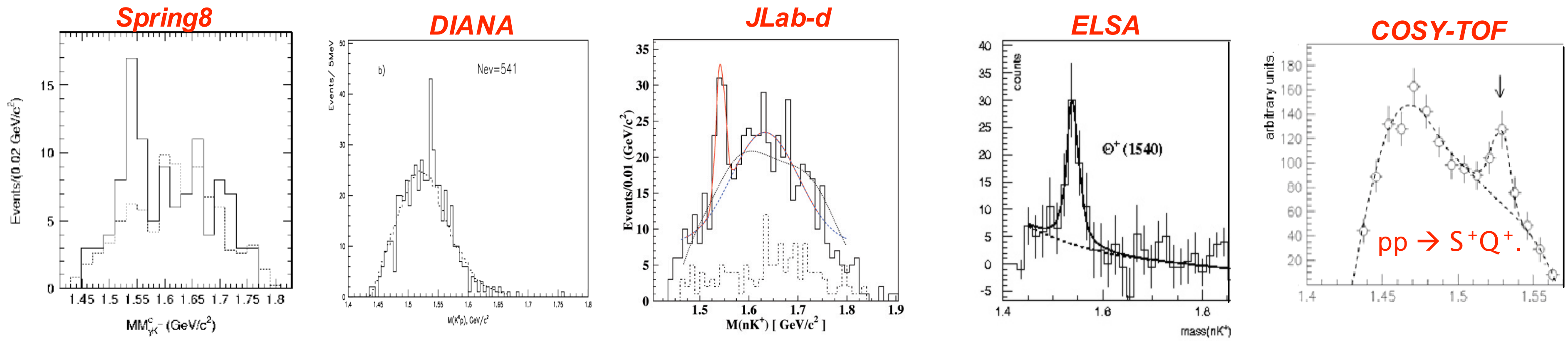


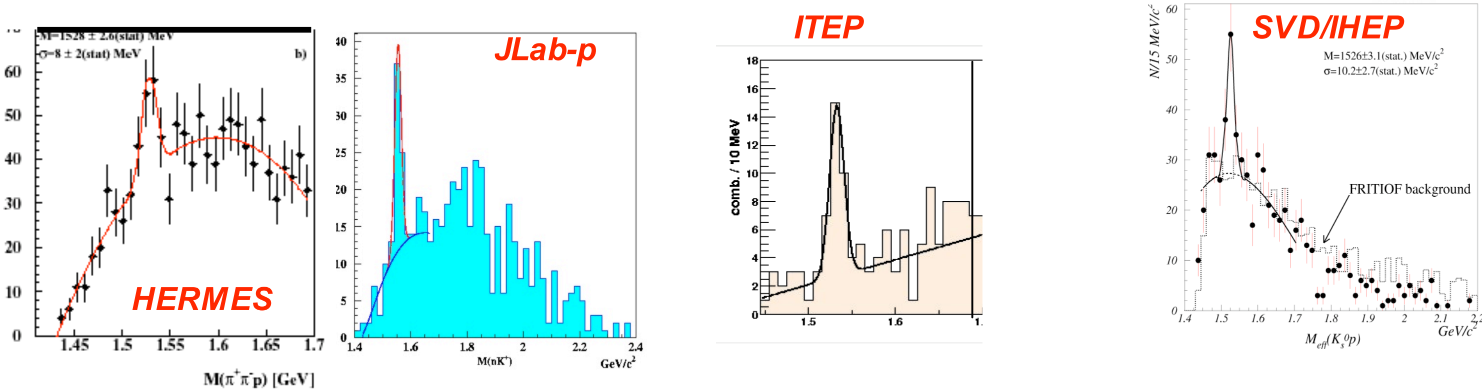
Θ decay is suppressed to the extent the 5-quark component of the neutron is less than its 3-quark component. Additional suppression comes from the peculiar flavor structure of the neutron's 5-quark component where the $\bar{Q}$ is in the flavor-singlet combination with one of the four Q.

A preliminary crude estimate gives $\Gamma_\Theta = 0.7\,\mathrm{MeV}$ without fitting any parameters!

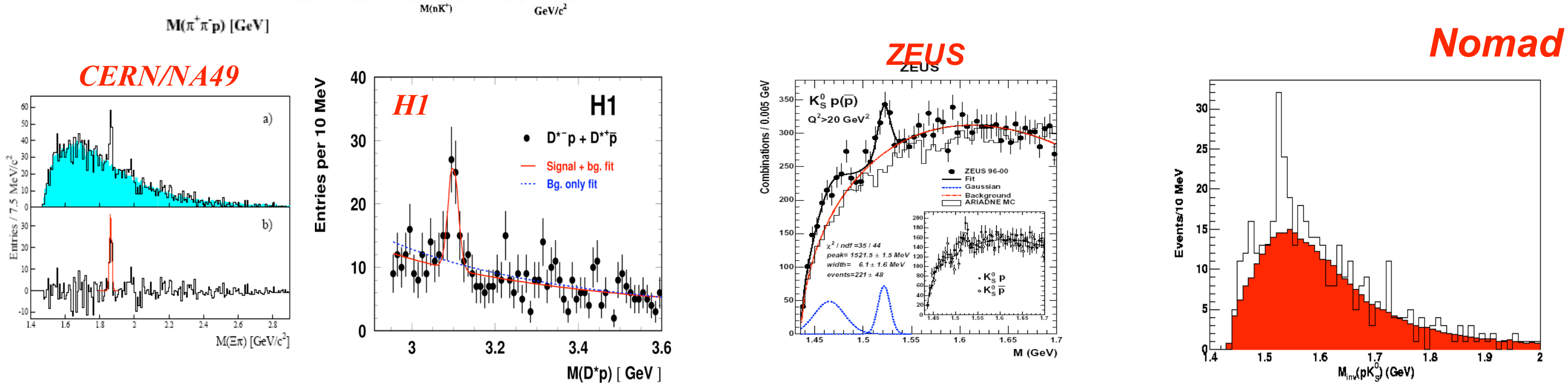
D. Diakonov, Talk at Pentaquak04

Evidence for Penta-Quark States

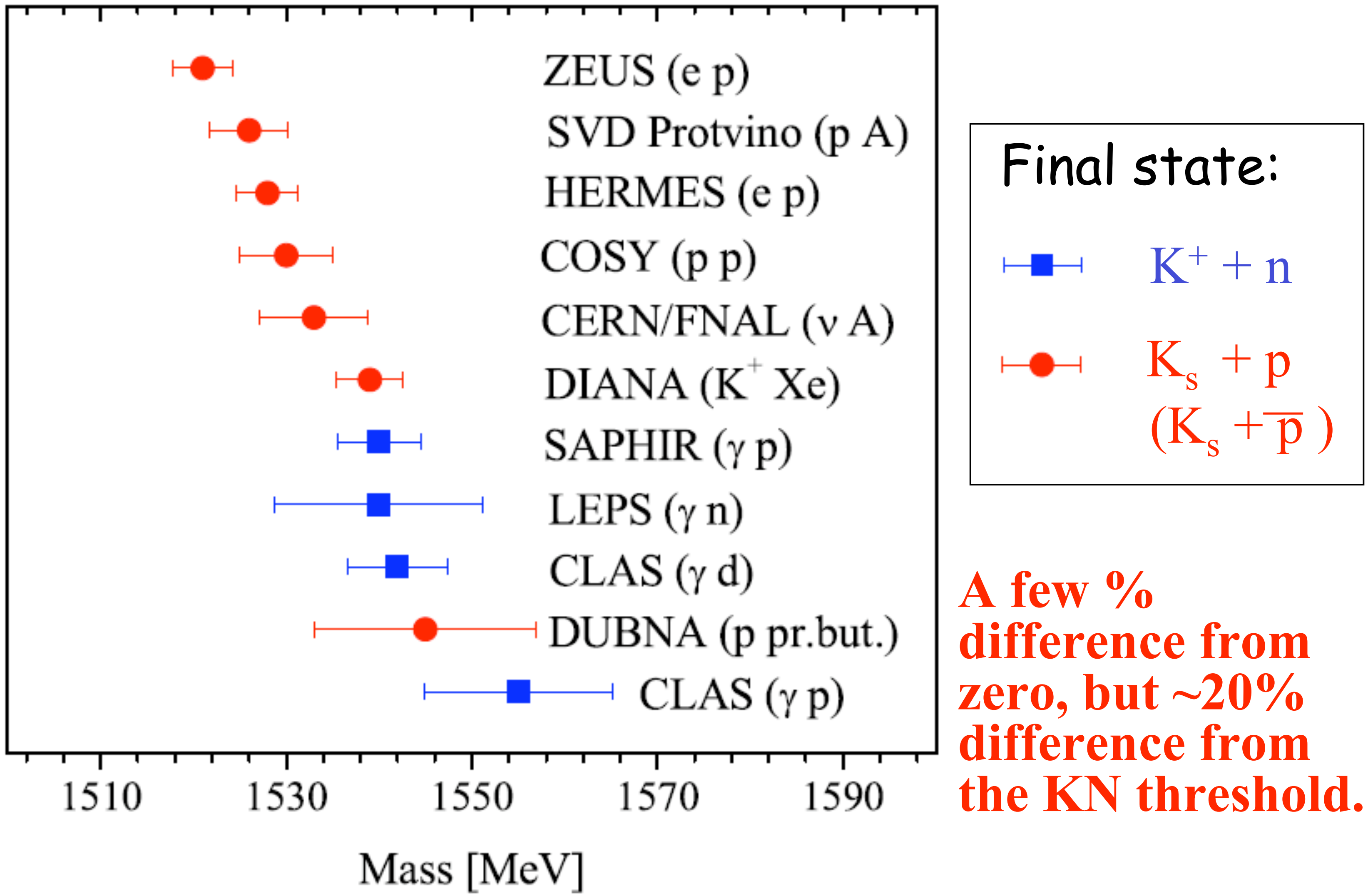




This is a lot of evidence. However,…



Mass



A few % difference from zero, but ~20% difference from the KN threshold.

Width

- **Again, there is inconsistency:**
  - **Most measurements give upper limits.**
  - **DIANA has G < 9 MeV.**
  - **The cross-section implies G=0.9 MeV.**
  - **HERMES: G = 13 +- 9 stat. (+- 3 sys.) MeV**
  - **ZEUS: G = 8 +- 4 stat. (+- 5 sys.) MeV**
  - **Arndt *et al.* and Cahn *et al.* analysis of KN phase shifts suggests that G < 1 MeV !!**
- **The small width is the hardest feature for theorists to understand…**

Null Results

- HERA-B (Germany):
  - reaction: p+A at 920 GeV
  - measured: K^-p and K^0p invariant mass
  - Clear peak for L(1520), no peak for Q^+
  - production rate: Q^+/L(1520)<0.027 at 90% C.L.
- BES (China):
  - reaction: $e^+e^- \rightarrow J/y \rightarrow Q^+\bar{Q}^-$
  - limit on B.R. of $\sim 10^{-5}$

And many unpublished negative results

(HyperCP, CDF, E690, BaBar, LEP,,,).

If the Q^+ does exist, its production in high energy reactions must be highly suppressed.

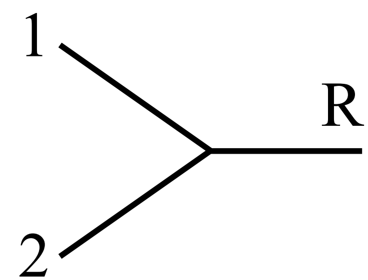
→ Model independent experimental search is most desirable.

We propose to

Search for the Θ^+ in **Formation** experiment with **High intensity** kaon beam and **Large acceptance** detector.

Cross Section for Formation

(Courtesy of M. Praszalowicz)



Breit-Wigner cross-section (GM + MP)

$$\sigma_{BW}(E) = \frac{2\overset{1/2}{\overset{\downarrow}{J}}+1}{(2\underset{\overset{\uparrow}{0}}{S_1}+1)(2\underset{\overset{\uparrow}{1/2}}{S_2}+1)}\frac{\pi}{k^2}\underset{\overset{\uparrow}{1/2}}{B_{in}}\underset{\overset{\uparrow}{1/2}}{B_{out}}\frac{\Gamma^2}{(E-M)^2+\Gamma^2/4}$$

$$\sigma_{BW}(M) = \frac{\pi}{k^2} \sim 16.8 \text{ [mb]}$$

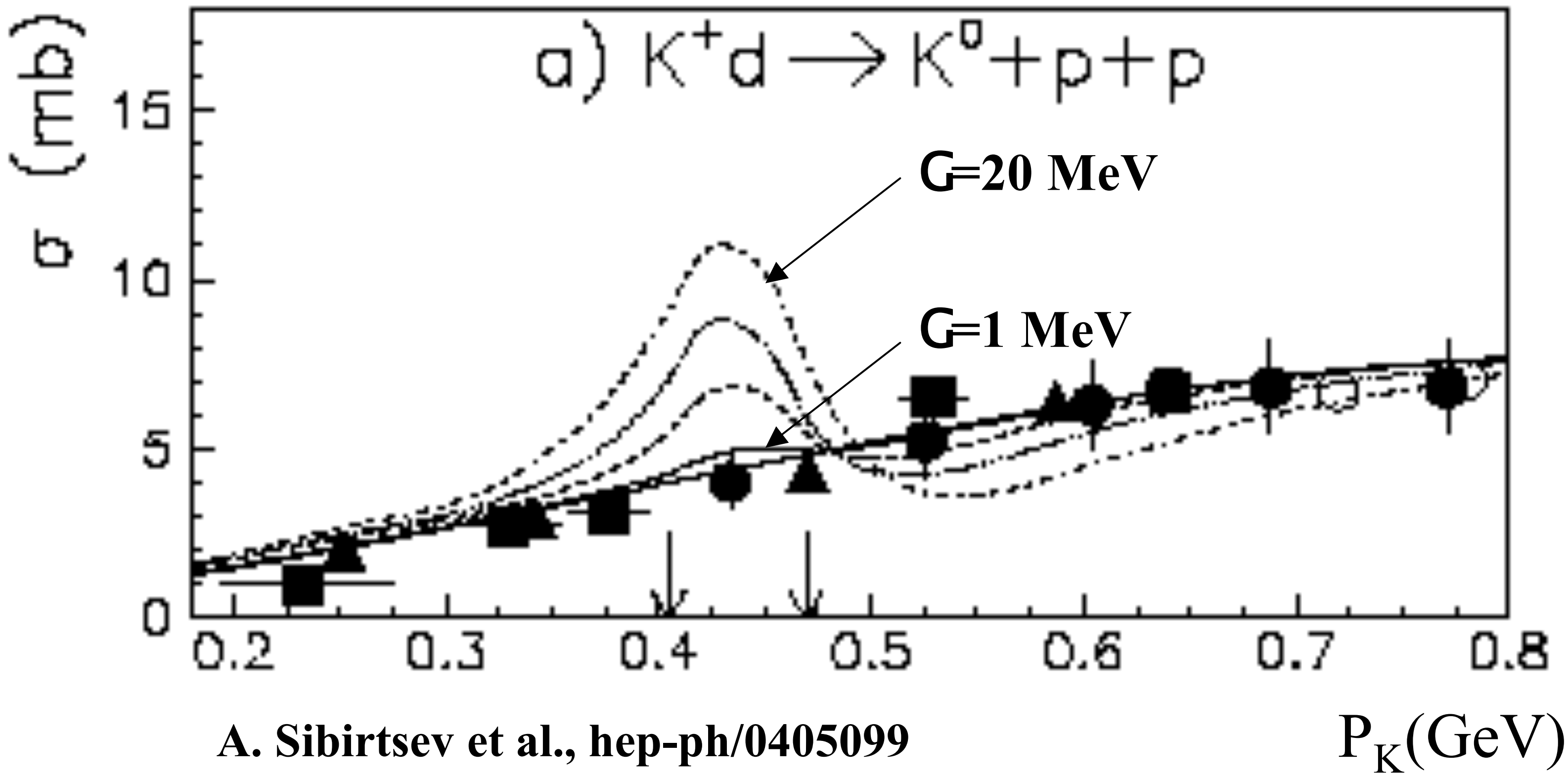
$$\boxed{\sigma_{BW}^{tot} = \frac{\pi}{4k^2}2\pi\Gamma \sim 26.4 \times \frac{\Gamma}{1 \text{ MeV}} \text{ [mb} \times \text{MeV]}}$$

Nussinov (hep-ph/0307357)

$$\sigma_{K^+n}(p) = \frac{4\pi}{p^2}\Sigma_l(2l+1)\ \overset{\text{C-G, not energy !}}{\overset{\downarrow}{E}}\ \sin^2\delta_l(p)$$

$$\sigma_{\Theta^+}|_{res} \simeq \frac{4\pi}{p^2}\cdot 3\cdot\left(\frac{1}{2}\right)\cdot\left(\frac{1}{3}\right) \simeq \frac{37}{2}\ \text{mb} \rightarrow 18.5$$

Cross section for "background"



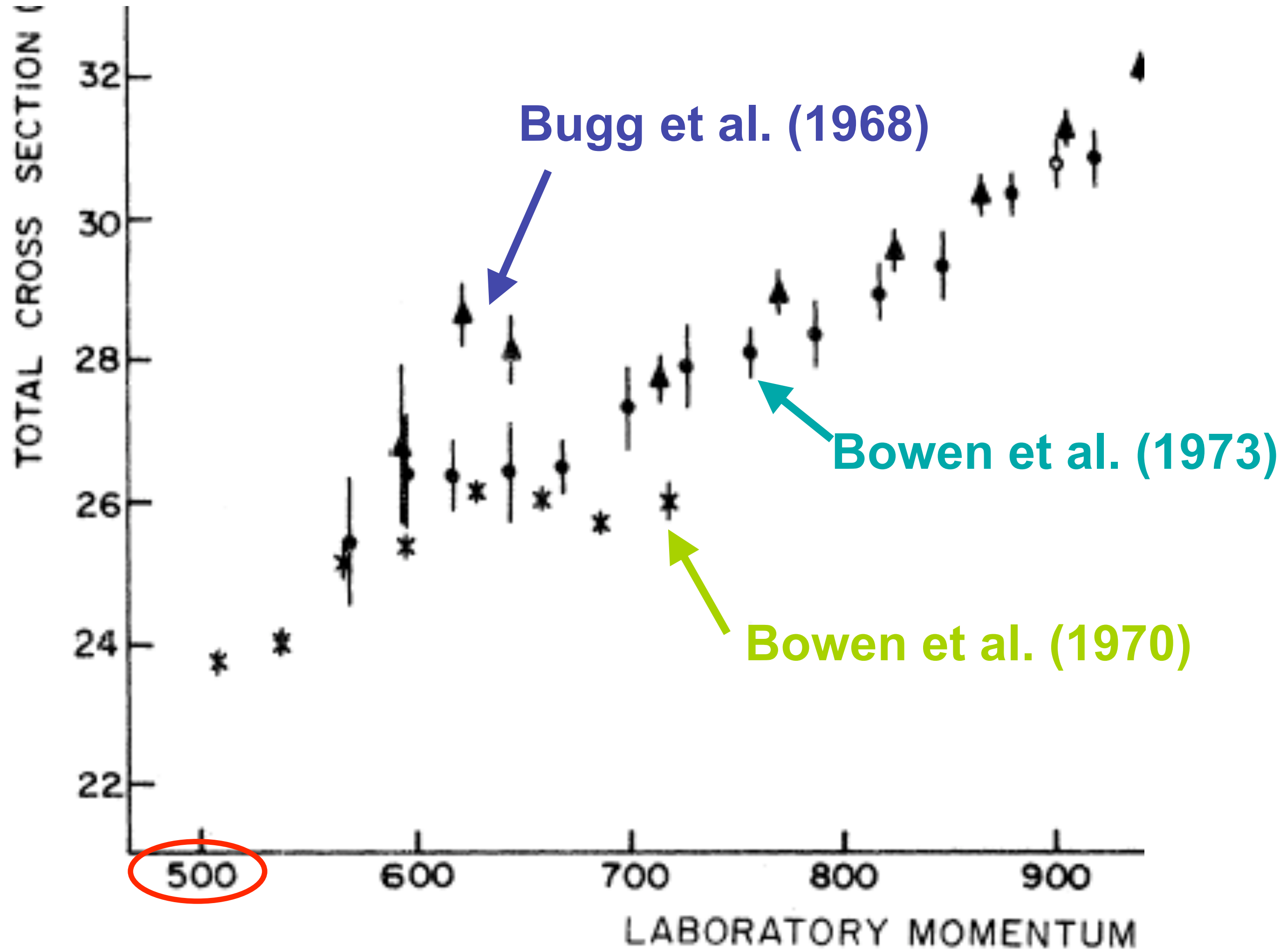
A. Sibirtsev et al., hep-ph/0405099

- The background is smooth and well known (~4 mb).
- The Q^+ with a narrow width should appear as a bump.
- If not, a strong limit on the width can be put.

The “noisy” K^+n database

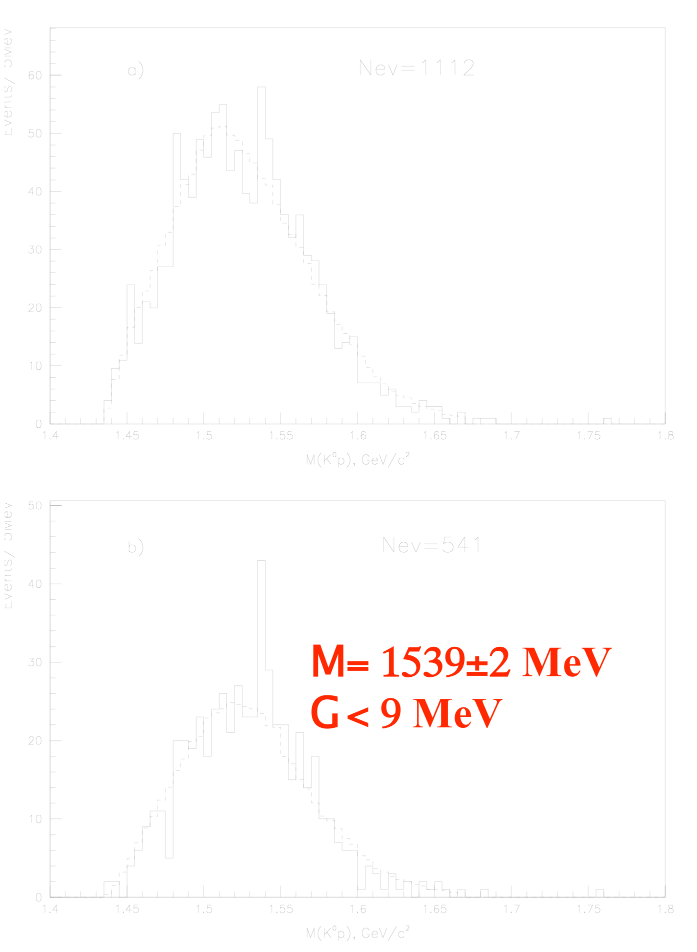
There are clearly some systematic problems in the KN data!

Note: errors get larger as momentum goes lower.



Previous formation experiment

K^+ Xe $\rightarrow$ K^0 p X
(K^+ n $\rightarrow$ K^0 p)



hep-ex/0304040

- **P_{K+} < 530 MeV/c**
- **Require q_K<100deg. & q_p<100 deg.**
- **Remove cos f $_{pK}$ <0 ← back-to-back**

K^+ n $\rightarrow$ Q^+ $\leftrightarrow$ Q^+ $\rightarrow$ K^+ n

$\boxed{G = 0.9 \pm 0.3 \text{ MeV}}$

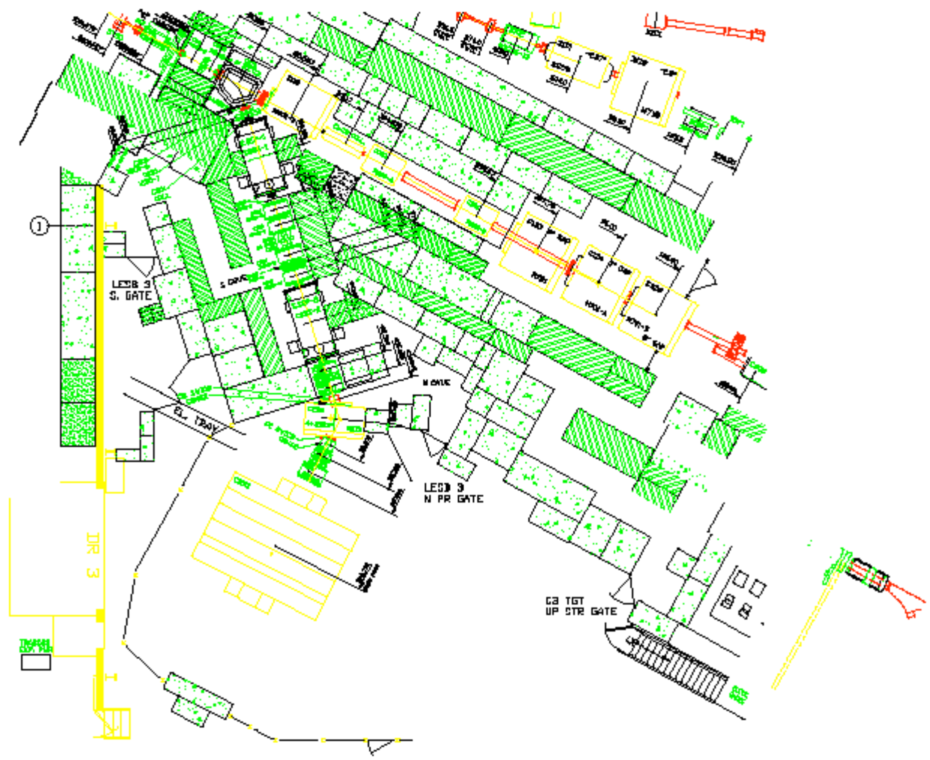
Cahn and Trilling hep-ph/0311245

consistent with KN phase shift analysis by Arndt et. al.

Phys. Rev. C68, 042201(R)

Kaon supply

•AGS will be running for polarized protons for RHIC.
• In principle, available between fills (i.e. most of the time). Flux of 10^{12} protons/spill should be easy (AGS ran at 60 times that for E949).
•LESB3 is a doubly-separated beam that goes up to 800 MeV/c.
•Can get 80% pure K^+.
•Can get 2.8×10^4 475-MeV/c K^+ per 10^{12} on target.



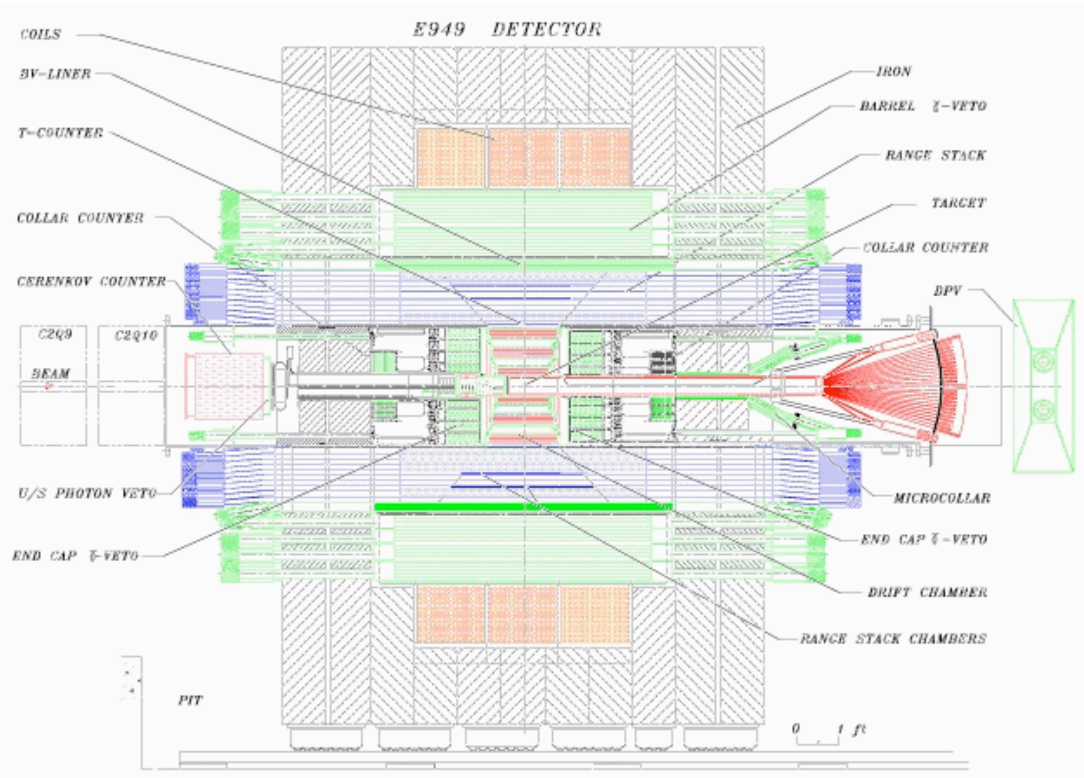
Technique

1. Trigger on K_S → p^+,p^-, measure in drift chamber + tgt.
2. dE/dx across 20cm width of tgt spans 40 MeV range in CM energy.
3. Reconstruct proton in target (& sometimes in chamber). Can get momentum except for sign of P_L (but usually is +) from transverse range + energy.
4. From K_S + p reconstruct center of mass - remove Fermi momentum.
5. Multiple cross-checks:
   - Excitation curve (already limits width to 1-2 MeV).
   - K_S missing mass technique
   - Some p's seen in the chamber.
   - Run at different momenta to cover wide range, decouple geometry from kinematics.
   - Run K- and study L(1520).

E949 Solenoidal Detector

•K$^+$ stopping target made of 400 5-mm square scintillating fibers. Can track and measure charged particles therein.

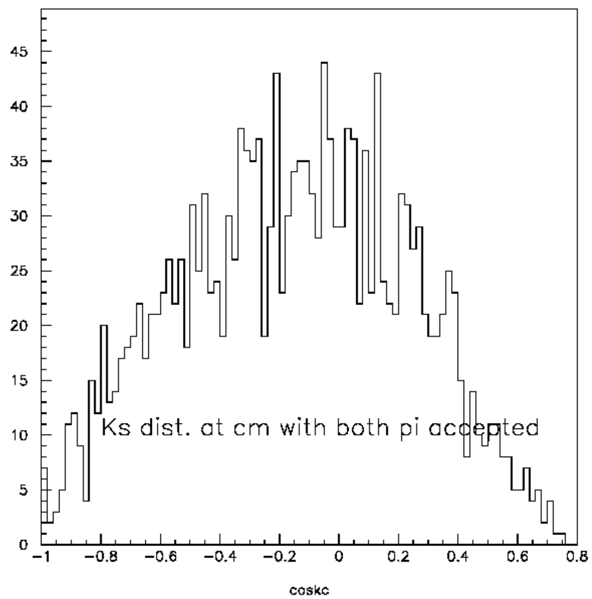
•Low-mass cylindrical drift chamber in 1-T field can measure momenta in this region to < 1%. In combination with target ~ 1.5%.

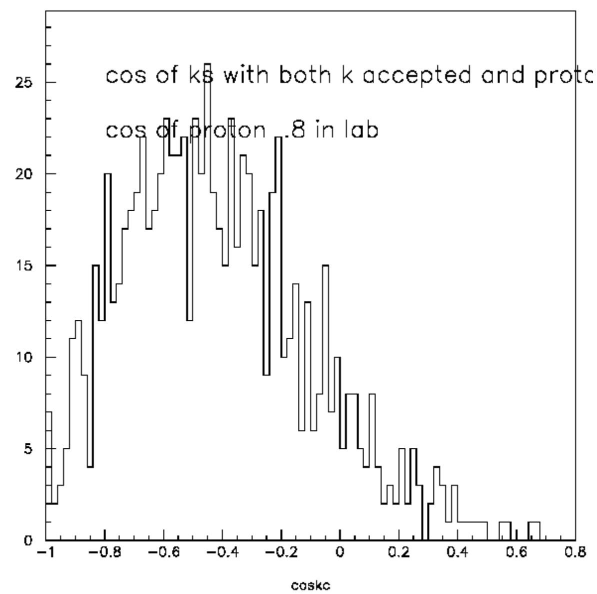


Elevation view of the E949 detector.

Monte Carlo of CM angle acceptance

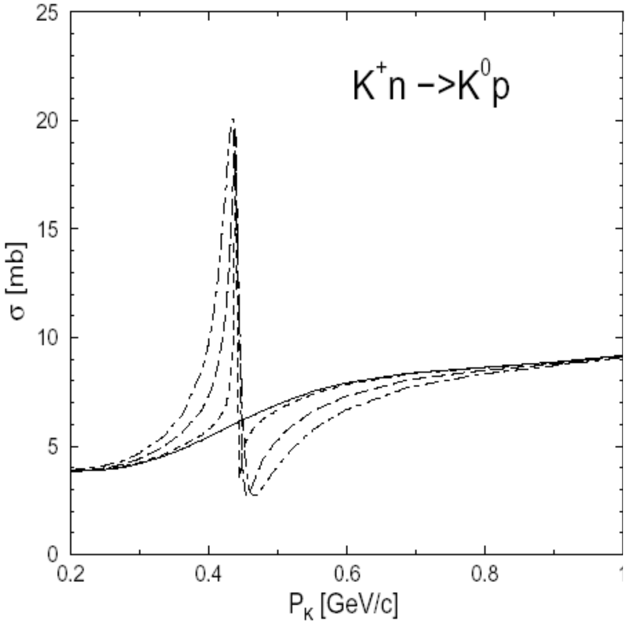
Distribution generated isotropic in CM

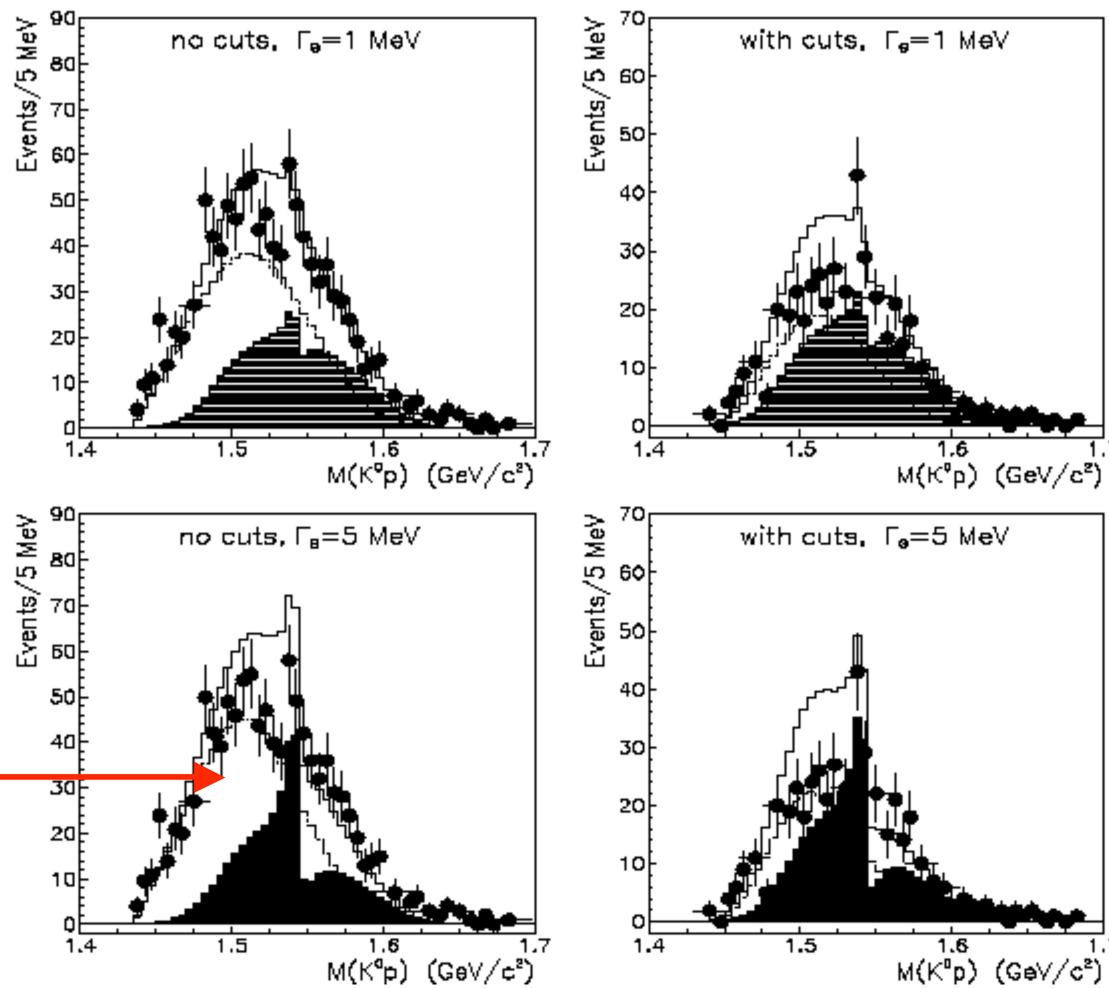




If the decay angle of the Q^+ is measured , its spin and parity may be determined through interference with BG.

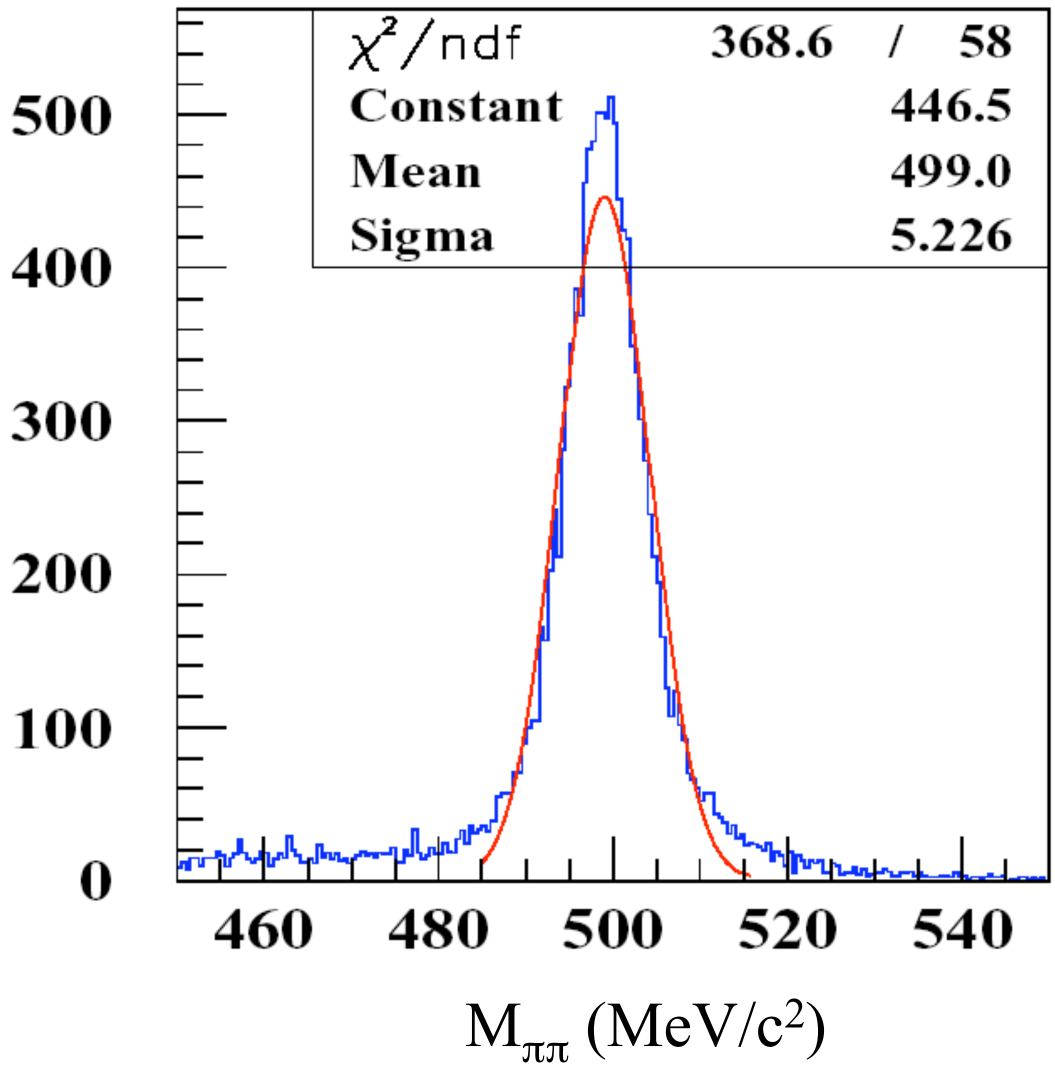
Interference





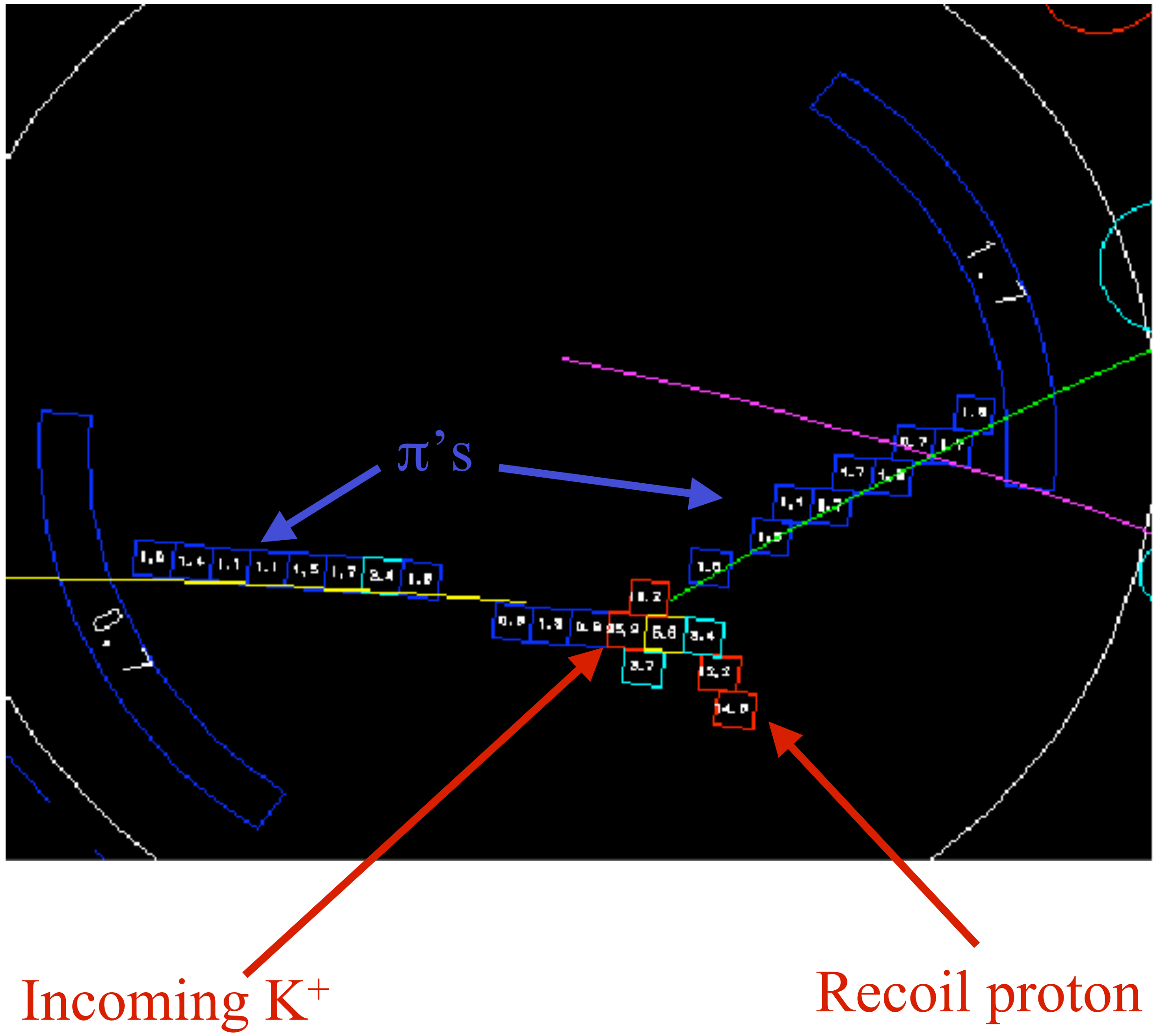
Sibirtsev et al. in nuc-th/0407011 claim very strong interference. Also v. large rescattering in Xenon. Note that we're working in C-12 vs Xe-131. Still need to worry about resolution!

$M_{\pi\pi}$ distribution from E949 showing $K_S \rightarrow \pi^+\pi^-$



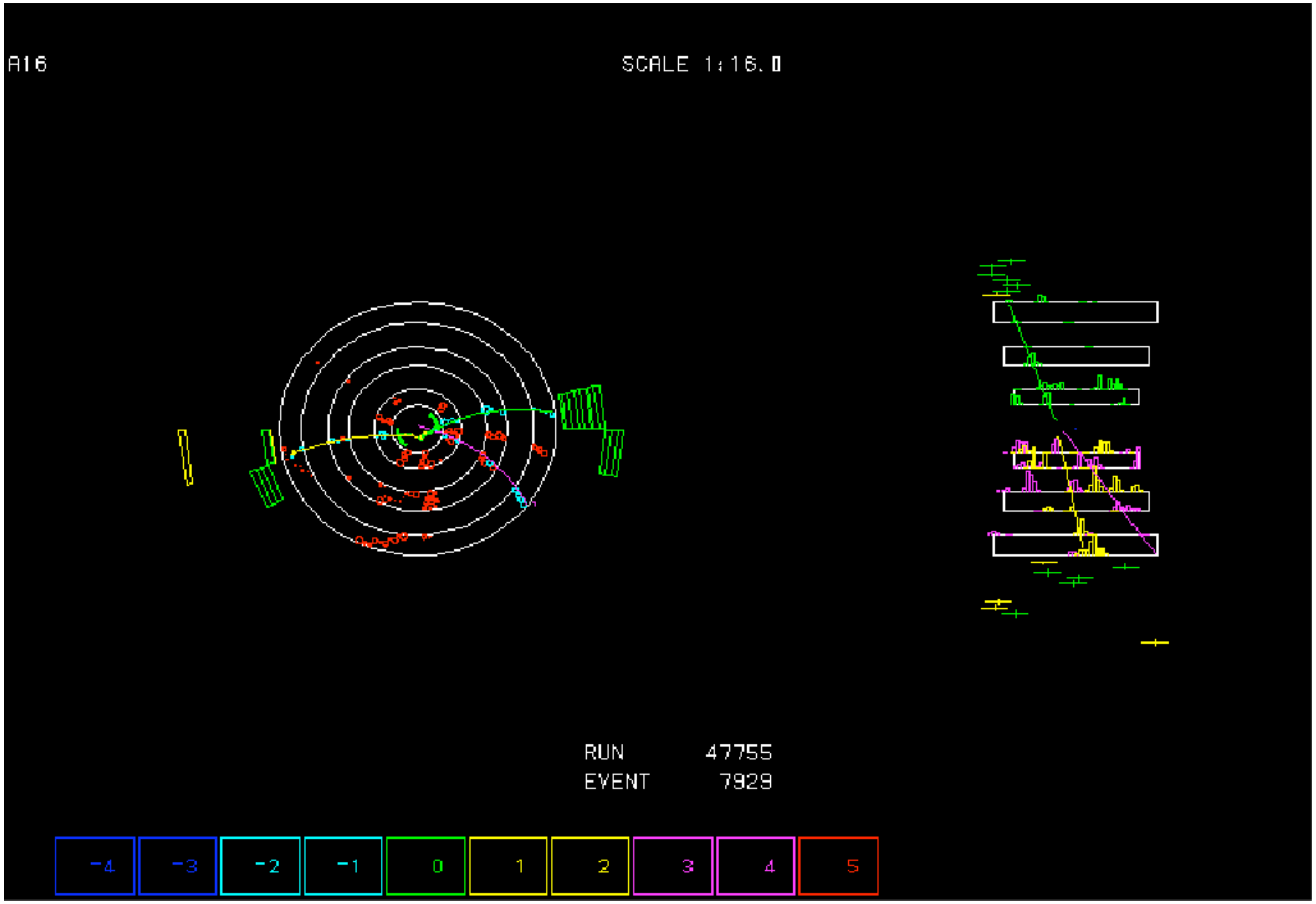
K_S candidate in the E949 target

Beam's-eye view of event in E949 target. Kaon enters at ~300 MeV/c. At this low momentum proton doesn't get very far



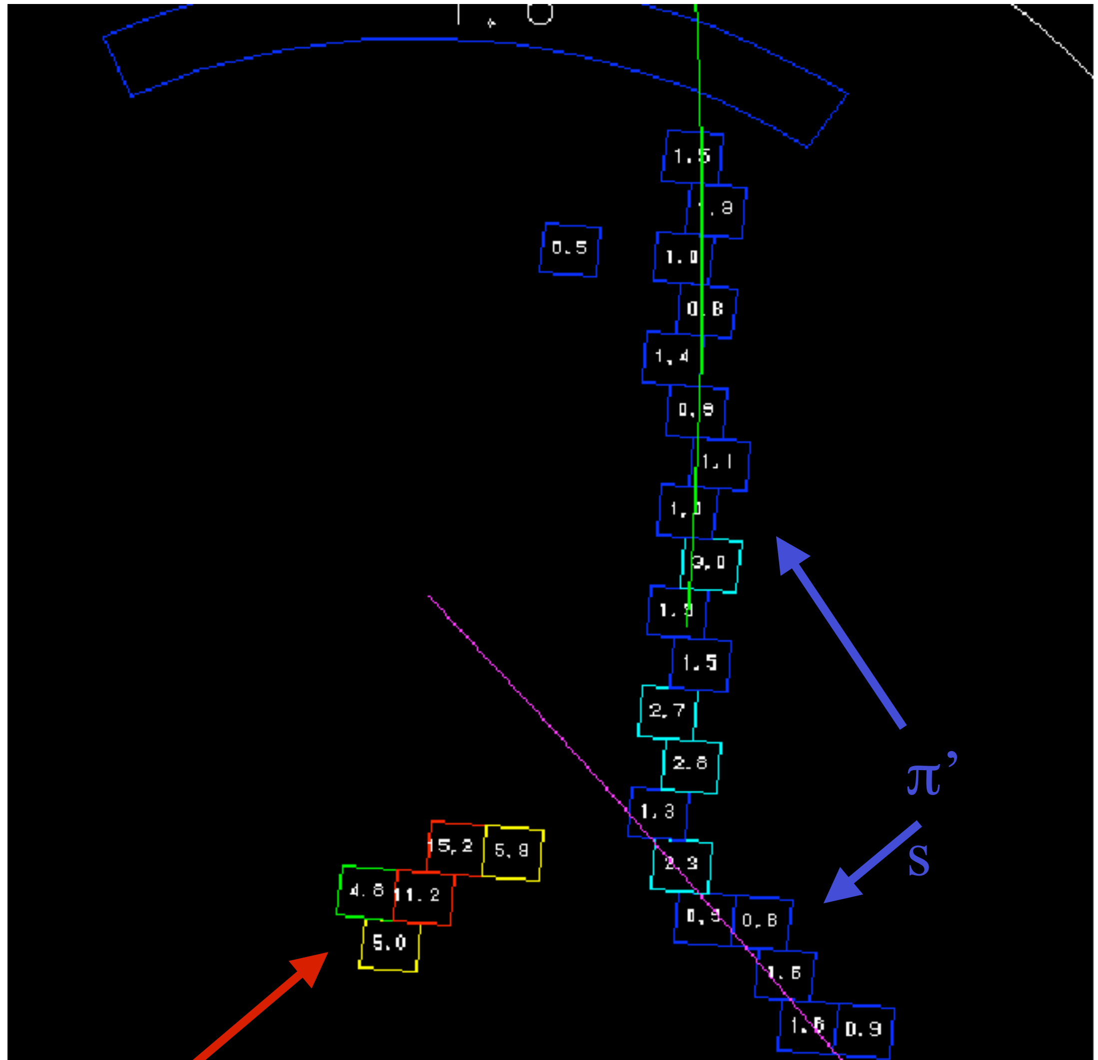
K_S candidate in the E949 detector

End and side views of event in E949 detector. Green rectangles outside of drift chamber are range stack scintillators with in-time energy. Purple drift chamber track is out-of-time random.



2^{nd} K_S candidate in the E949 target

Beam's-eye view of 2^{nd} event in E949 target. This time the recoil proton either overlaps the incoming K or is absent

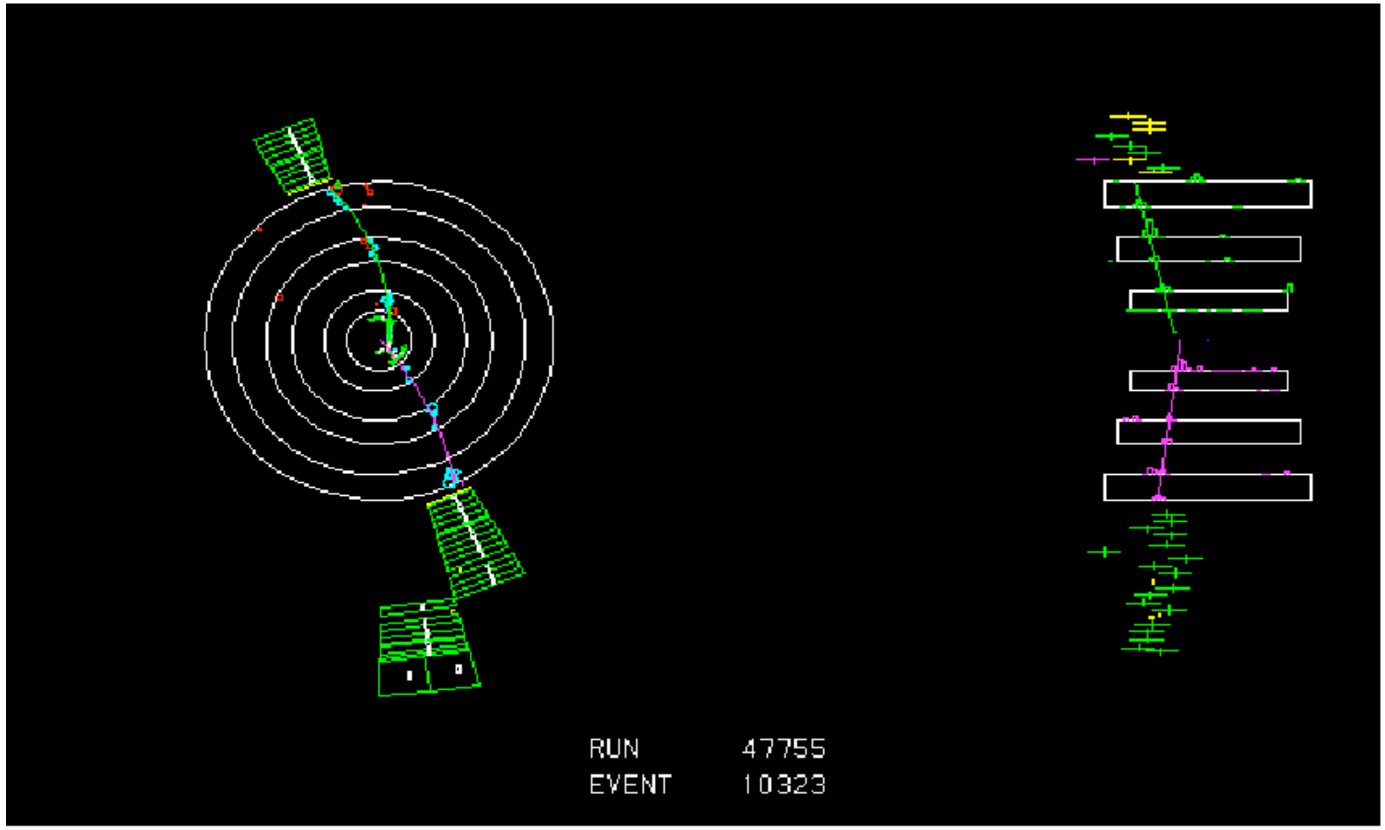


π's

Incoming K^+

2nd K_S candidate in the E949 detector

End and side views of event in E949 detector.



Rates

1. "Background" rate ~800 K_s/pulse.
2. For Q^+ width 1MeV, integrated cross-section is 26.4mb-MeV, which would give about 1/6 as many events, 1/10 with K_S into p^+,p^-.
3. AGS spill to be optimized, assume e.g. 1.3sec/3.6sec, gives 10^5 spill per 100 hours or 8M produced Q^+ per 10^{12} POT for 1-MeV width.
4. Acceptance for K_S ~ 10%, so 800,000 Q^+/week in which we see K_S. Proton acceptance not yet known, but geometrical acceptance high. Overall shouldn't be <10%, so at least 80,000 Q^+/week, going in.

Running requests : ~ 10^{12} POT for 5 weeks

- need to get detector on air, vary momenta, do K^- runs.

Things to do

-before deciding if a proposal is warranted.

- Detailed Monte Carlo & studies of E949 data to get resolutions and acceptances. Requires mods to E949 software.
- Studies of pattern recognition in target
- Fine tuning of strategy